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Assessment of HVAC Installations in New Homes in Southern California Edison's Service Territory

Prepared for:
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

In 1994, Proctor Engineering Group investigated opportunities for improving air conditioning system performance in new residential construction in Southern California Edison’s service territory. This investigation involved field testing duct systems, air handlers, and building shells in 10 houses; assessing achievable improvements to the systems; and analyzing the potential energy savings and peak demand reductions from such improvements. The investigation found substantial deficiencies in most of these systems. Duct leakage and existing duct insulation levels cause an average effective capacity loss of 33%. Air handlers often provided insufficient air flow across the indoor coil. A package of moderate cost improvements was recommended that would lower energy usage and demand with improved occupant comfort and satisfaction.

EXECUTIVE SUMMARY

Southern California Edison (SCE) contracted with Proctor Engineering Group (PEG) to investigate opportunities in the Palm Springs area of SCE's service territory for improving air conditioning system performance in new residential construction. This investigation has involved field testing the duct systems, air conditioners, and building shells of a sample of newly built houses; assessing achievable improvements to the systems; and analyzing the potential energy savings and peak demand reductions from such improvements. The investigation found that newly constructed homes in the Palm Springs area have substantial deficiencies in their distribution systems, similar to those found in studies from other parts of the country (Appendix A contains brief descriptions of related studies). Improvements can be made to provide lower energy usage and reduced demand while improving occupant comfort and satisfaction. These improvements can be accomplished at moderate cost.

The key findings of this study include:

- Duct leakage and existing duct insulation levels cause an average loss of 33% in overall cooling efficiency. Reasonable improvements can eliminate over half of these losses (save 18% of the cooling energy) for about $235;
- A program which ensures tight, well-insulated ducts and properly installed efficient air conditioners could reduce cooling usage by approximately 44% and diversified peak demand by 1.2 kW. The additional cost is estimated to be $650 per unit;

SCE has a variety of potentially worthwhile options to pursue for improving cooling efficiency and reducing peak demand. Proper program design, training, and quality assurance are critical issues for actually achieving these improvements. These topics are the focus of a follow-up report under this project.

BACKGROUND

Southern California Edison (SCE) contracted with Proctor Engineering Group (PEG) to assess the energy savings and peak demand reductions achievable from an air conditioner system efficiency program targeted to new residential construction in SCE's service territory. This assessment involved the following:

- detailed field testing of a sample of 10 newly built homes in the Palm Springs area to identify problems with current installation practices;
- a determination of achievable improvements to current practice and the costs of those improvements;
- an engineering analysis of field data to estimate the impacts of potential improvements on energy usage and peak demand, and;
- an implementation plan for changing current practice.

This report describes the activities and results from the first three items.

PRIOR RESEARCH

PEG's prior experience, and the findings of other research projects around the country (see Appendix A), has found that typical air conditioner system installations have numerous problems which adversely impact efficiency, demand, and comfort. The primary problems identified include:

- excessive duct leakage in unconditioned spaces leading to substantial loss of conditioned air, heated return air, and increased house infiltration;
- insufficient air flow across the indoor coil;
- incorrect refrigerant charge;
- excessive system oversizing.

In prior studies, these problems were found to be common, not unusual, circumstances. Duct leakage has become a significant concern in the recent past. Studies from California, Florida, and the Pacific Northwest have consistently found large efficiency losses due to typical levels of duct leakage. The problems associated with incorrectly installed air conditioners has had less exposure however studies in California, Nevada, North Carolina and Massachusetts have shown major efficiency solles due to incorrect change and air flow on heat pumps and air conditioners.

FIELD INVESTIGATION

Trade practices and housing styles vary throughout the country and so do the relative frequency and severity of different air conditioner and distribution system installation problems. In addition, other problems or savings opportunities may be as or more important in SCE’s service territory than those listed in Appendix A. A field investigation of newly constructed houses in SCE’s service territory was needed to characterize the local problems and opportunities.

Proctor Engineering Group examined 10 newly-built houses in the Palm Springs area. SCE recruited two local builders and provided a list of 10 houses from two sub-divisions in the Palm Springs area. Houses were sought which were not yet occupied but fully completed. Unfortunately, the identified sites did not yet have power when tested and only 110V temporary power was available. Therefore, tests which require fully operating the air conditioning equipment (i.e., assessing charge and/or identify operating anomolies) could not be performed. The two sub-divisions differed in construction styles and, while not necessarily a representative sample, are not considered unusual for new construction in the area.

FIELD DATA COLLECTION PROTOCOL

PEG designed the field investigation to examine a wide variety of potential HVAC problem areas. The field procedures included many recently developed state-of-the-art diagnostic tests (particularly for assessing the duct systems). The field testing protocol is summarized in Table 2-1. Copies of the field data collection forms are attached as Appendix D.

IMPLEMENTATION

Highly trained, efficient and organized field technicians were needed to perform the field work within the project’s time and budget constraints. PEG contracted with Conservation Services Group (CSG) to perform the work. The lead technician had been previously trained by PEG and was experienced with PEG procedures. All technicians were carefully trained by PEG to ensure high quality data for the study.

Two person teams required an average of half a day per house. Nine of the ten sites were tested in the June and one site was tested in July.

Table 2-1
Summary of Field Test Procedures

Parameter	Tests	Description / Use
Duct Leakage	Duct Blaster™ - total leakage	pressurize ducts to 25 pa with registers sealed, measure fan flow, check pressures in other parts of duct system
	Duct Blaster™ - exterior leakage	repeat above test while blower door pressurizes house to 25 pa, eliminating pressure difference between ducts and house
	Half Nelson - return/supply leakage split	measure pressures in supply and return plenums with air handler on and registers sealed - results used to adjust duct blaster results into supply and return leakage rates
Air Handler Flow	Duct Blaster™ - pressure replication method	seal off return and use duct blaster in its place as a powered flow hood to replicate supply plenum pressure measured from normal air handler operation - required flow equals normal air handler flow
	Operating Static Pressures	measure static pressures in supply and return plenums - used in air handler flow test above, for adjusting duct blaster results to estimate supply and return leakage fractions when air handler operates, and for assessing duct design
AC Capacity[1]	Enthalpy Change across AC coil	measure wet and dry bulb temperatures in supply and return plenums - when combined with air handler flow rate can calculate actual capacity (under test conditions, which can be adjusted to ARI standard)
AC EER	Wattage Input	use house electric meter to measure actual electric input to AC, calculate EER at test conditions by dividing input into capacity
AC Charge	Superheat / Subcooling	measure subcooling, superheat, head pressure, hot gas discharge temp., outdoor unit delta T, and power draw - compare to manufacturer target values when possible. Assess charge from available evidence including air handler flow rate, capacity, input, measured EER
AC other	miscellaneous	collect nameplate information from indoor and outdoor units, assess potential outdoor unit air recirculation
Duct Conduction	Duct System Location	Estimate percentage of supply and return ducts in various locations (attic, garage, inside, etc.) - used to estimate ambient conditions around ducts for modeling conduction and leakage
Building Airtightness	Blower Door Test	Measure CFM_{50} of house, also measure pressures developed in key building zones such as attics

CSG's field manager and PEG staff reviewed all data. The data were entered into spreadsheets, further analyzed for quality, and then calculations were performed to derive the system parameters of interest.

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[1] The air conditioner tests shown shaded in the table could not be performed because the sites did not yet have 220V power available.

FINDINGS - GENERAL CHARACTERISTICS

There were two primary types of houses in the study- one story houses in a sub-division in Cathedral City and two story houses in a sub-division in Palm Desert. The typical house was slab-on-grade construction with 3 bedrooms, about 1540 square feet of living space, double-glazed windows and R-30 attic insulation. The one story houses had their air handlers located in the garage with all supply ductwork in the attic and a single return duct running from a hallway ceiling grill through the attic and into a garage platform. The two story houses had the air handlers located in the attic with a short return run through the attic from a hallway ceiling grill, second floor supply runs in the attic, and first floor supply runs located within the walls and floors of the conditioned space. Locating an air handler in the attic exacerbates the impacts of any return system leakage and increases conductive heat gains.

The houses were fairly tight, with an average blower door measured air leakage rate of 1970 CFM50 (Cubic Feet per Minute at a pressure difference of 50 pascals). The one story houses were tighter than the two story; leakage rates averaged 1690 and 2250 CFM50 respectively. Tight construction reduces heating and cooling loads, but may not provide for sufficient ventilation. If ASHRAE standard 62-1989 is applied to modeled average ventilation rates, none of the one story houses meet the minimum infiltration criteria of 0.35 Air Changes per Hour (ACH).

FINDINGS - DUCT SYSTEMS

The duct systems commonly consisted of 6”-8” supply runs and 14” to 20” return runs of R-4 flex duct. The one story houses had platform returns in the garage which were quite leaky and were often connected to the return grill via a combination of building cavities (e.g., wall stud spaces and dropped ceiling) and flex duct. During the testing, the technicians noted that most of the duct systems had obvious and easily eliminated leakage at the plenums, boot connections and air handler. They also noted that existing connections may be subject to future failure because they were made with duct tape. Therefore, the systems were tested when they were as tight as they will ever be. They can be expected to leak more over time due to tape failure and disturbances (i.e., disconnections and tears) caused by cable TV and alarm system installers.

Detailed duct leakage measurements were used to quantify the magnitude and impact of the existing leakage problems and the opportunities for improvement. Duct leakage can be measured in several different ways (Proctor et al, 1994). Total leakage and leakage to the exterior at a particular test pressure are both directly measurable in most houses, but actual leakage flow rates to the exterior during normal system operation, split between supply and return, must be estimated to calculate the energy and peak effect of duct leakage.

The total duct leakage test establishes the leakage rate of the duct system at a specific pressure difference (usually 25 or 50 pascals) by measuring the air flow needed to establish that pressure difference across the ducts when all registers are sealed. The total duct leakage test is a relatively fast and repeatable test method that is easily applied to new construction even before the drywall is installed. In this study, total duct leakage was tested using a Duct Blaster™ (a trademark of the Energy Conservatory). The average measured total leakage rate was 379 CFM50. The distribution of total duct leakage is shown in Figure 2-1.

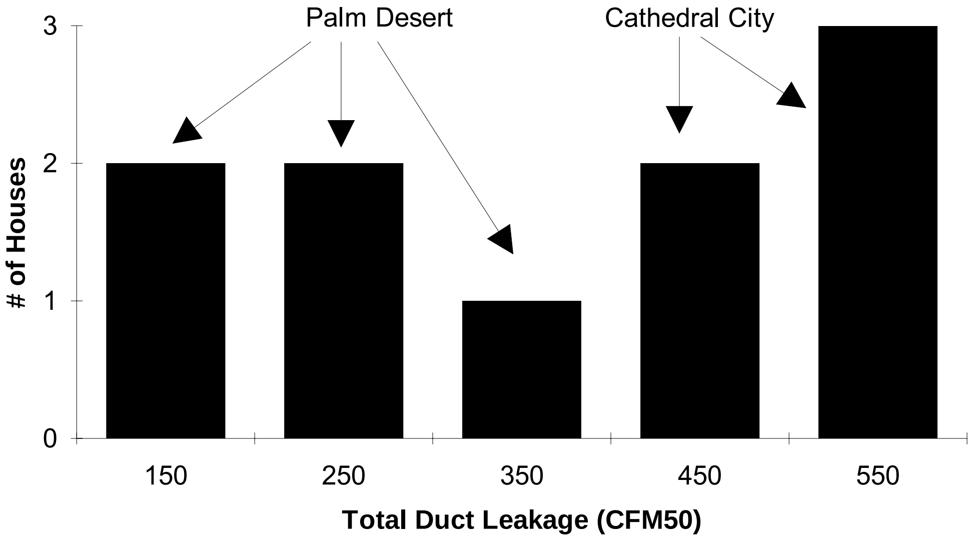

Figure 2-1
Total Duct Leakage

The five leakiest systems, ranging from 423 to 586 CFM50, were the five one story houses tested in Cathedral City. The five tightest systems, all in Palm Desert, ranged from 184 to 305 CFM50. The large difference in leakage rates between the two locations is primarily in the return side of the systems; the Cathedral City houses average 321 CFM50 of total return leakage while the Palm Desert houses average only 96 CFM50. The Cathedral City return systems are leakier because they have longer runs, use building cavities as part of the duct system, and connect to leaky garage platforms.

Duct leakage to (and from) the exterior is a better measure of duct leakage problems than the total leakage measurement, but involves more difficult and time-consuming tests. In this study, exterior duct leakage was measured using a blower door and a Duct Blaster™ to pressurize both the building and the ducts to the same pressure simultaneously. This reduces the duct leakage to inside to a minimum and thus measures the duct leakage to the exterior. The distribution of exterior duct leakage is shown in Figure 2-2.

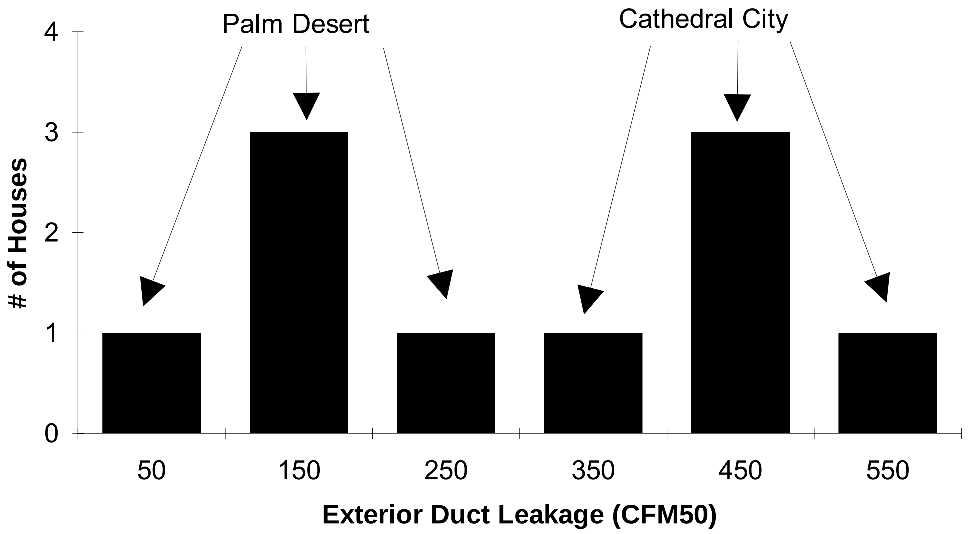

Figure 2-2
Duct Leakage to the Exterior

The average leakage to the exterior is 292 CFM50, comprising about 16% of total building leakage on average, slightly tighter than the duct leakage rates found in studies of existing housing in California and Florida (SOURCE: Proctor, 1991; Tooley & Moyer, 1989). Again, the one story houses'duct systems were all much leakier than the two story houses' systems, averaging 441 and 144 CFM50 of exterior leakage respectively. The difference between the two groups of houses in exterior leakage rates is greater than the difference in total leakage rates because a greater proportion of the 2 story houses' duct systems are located within the conditioned space. Combined with the fact that the one story houses had tighter building shells, their duct systems accounted for 23% to 30% of total house air leakage while the two story houses' systems were responsible for only 5% to 9% of their house leakage rates.

Both the duct leakage to outside and the total duct leakage tests are useful in measuring the size of the holes in the duct system. However, the key quantities which impact energy usage are the supply and return leakage under normal operating conditions (usually expressed as a percentage of the total system air flow). In this study, exterior leakage was allocated to the supply and return sides based on the half Nelson test and the proportion of each side of the system that was within the conditioned space. The operating leakage for each side was then calculated by adjusting the leakage rate to the average operating static pressure in that side of the duct system[2]. Finally, the operating leakage estimates were divided by the measured system air flow through the coil. The supply and return operating duct leakage rates are summarized in Figure 2-3. The flow

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[2] The flow exponent was assumed to be 0.65. The leakage at operating conditions therefore was calculated as Test Flow * (operating pressure/test pressure)^.65

rates averaged 83 cfm for supply leakage and 182 cfm for return leakage, representing about 6.7 and 14.5 percent of the air handler flow.

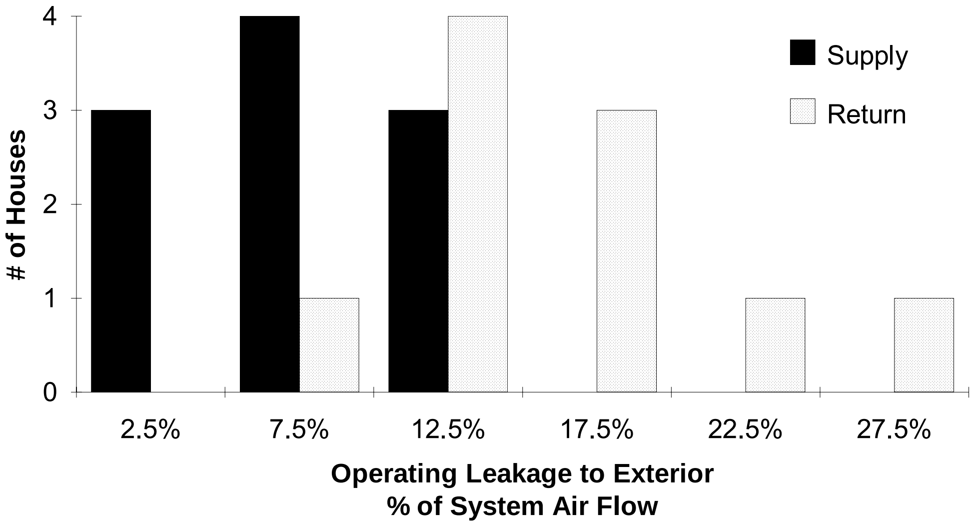

Figure 2-3
Supply and return leakage to exterior as a percentage of system air flow

Again, the Cathedral City houses' duct systems are much leakier than those in Palm Desert. Supply leakage fractions averaged 9.5% and 4.1% and return leakage fractions averaged 20.8% and 11.6% respectively. Although the Palm Desert return systems were quite tight as measured by CFM50 to the exterior, they still had fairly high leakage fractions because they operated with very high static pressures (caused by undersized ductwork).

FINDINGS - AIR CONDITIONING SYSTEMS

Each sub-division had a single brand of air conditioner with capacity variations related to conditioned space. The smallest houses (1250-1472 sq.ft.) all had 3.5 ton units, three mid-sized houses (1534-1691 sq.ft.) had 4 ton units, and the two largest houses (1820 sq.ft. each) had 5 ton units. The rated SEERs of the units ranged from 10 to 10.8.

PEG had planned to test the air conditioning units with a detailed protocol in order to assess air flow across the indoor coil, refrigerant charge, and miscellaneous other potential operating or efficiency problems. However, the lack of 220V power at the sites limited testing and data collection to procedures which do not require operating the compressor. As a result the units could not be checked for proper refrigerant charge. Instead, the impacts of over and undercharged systems and fixes to these problems was assessed through modeling different scenarios based on data collected in similar studies of new construction elsewhere.

Air Handler Flow Rate

The proper operation of an air conditioning system depends upon providing the correct air flow rate across the indoor coil—usually 400 cfm per ton of nominal capacity. In a hot/dry climate such as Palm Springs, where sensible cooling is almost the exclusive goal of air conditioning, higher air flow rates are recommended by Air Conditioning Contractors of America (ACCA). Low air flow has been a common problem found in other studies of air conditioner performance (Proctor, 1991; Neal, 1990). In addition to potentially shortening equipment life, incorrect air flow renders most standard tests for proper refrigerant charge invalid.

System air flow rates were assessed using a recently developed approach which employs the duct blaster as a powered flow hood. The procedure involves sealing off the return grill and mounting the duct blaster so that it acts as the return. The air handler is then turned on and the static pressure in the supply plenum is measured. The duct blaster fan is then also turned on and adjusted until the supply plenum pressure equals the pressure which was measured during normal system operation. When the pressures are equal, the flow through the duct blaster equals the normal air flow of the system. Figure 2-4 shows the distribution of measured flow rates compared to manufacturers' specifications (for the eight units where tests could be completed). The measured flow rates ranged from 253 to 352 cfm per ton and averaged 319 cfm per ton, about 20 percent below the target value of 400. All but one unit tested was below 350 cfm/ton , a level often considered requiring corrective action.

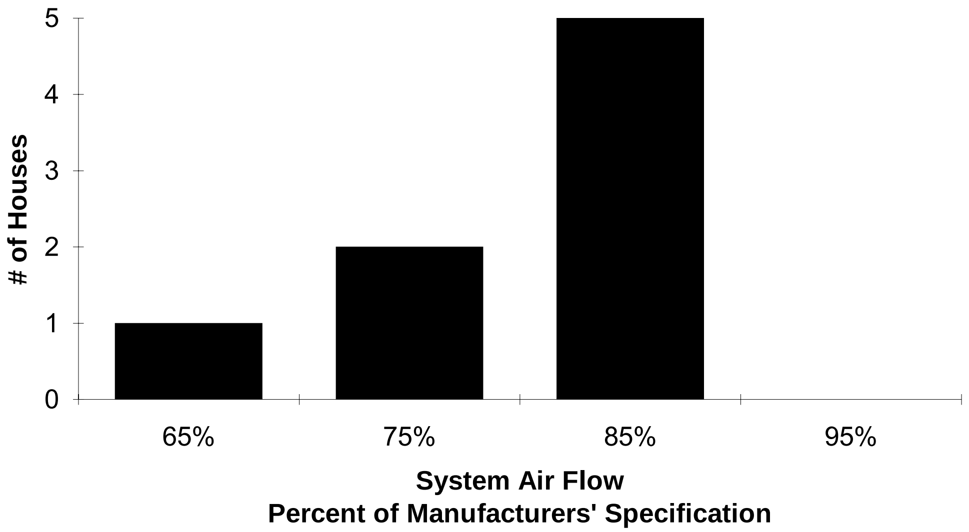

Figure 2-4
System Air Flow as a percentage of manufacturers' specification

Causes for the low air flow rates were investigated. ACCA Manual D specifies that the cooling capacity of the equipment should not exceed 30,000 Btu/hr per filter grill. All of the units were larger than 30,000 Btu/hr, but none had more than one filter grill. Manual D also suggests that the typical static pressure difference from before the fan to after the coil is 100 pascals (0.40 inches of water column). The systems averaged 182 pascals on the Palm Desert houses and 89 pascals in the Cathedral City houses.. The Palm Desert houses had noticeably undersized return ductwork (e.g., a single 14 inch diameter round flex duct for a 5 ton air conditioner) and averaged only 311 cfm of air flow per ton of air conditioning capacity.

Air Conditioner Sizing

Full scale design load calculations were not a part of this study, however, based on a quick check of floor plans, insulation values, orientation and glazing the cooling loads at design conditions probably ranged from 19,000 to 27,000 Btu/hr with an average of approximately 22,000 BTU/hr.

The 97.5% design conditions for Palm Springs are 110°F dry bulb and 70°F wet bulb outdoors and 75°F dry bulb indoors. The very low outdoor humidity at design (less than 15% RH) means that the latent load will be near zero. The capacity of the installed equipment at design conditions was estimated by using an approach developed by PEG (based on manufacturer’s data and research) to adjust the standard rated values (which are based on wet coil, 95ºF outdoors, 80ºF indoors) to account for a dry coil with 110°F outside and 75°F inside. This adjustment typically reduces the rated capacity by about 25%. Based on this approach, the average design capacity of the installed equipment is 34,000 Btu/hr, yielding an average oversizing of 41% when compared to the calculated design loads. This amount of oversizing is somewhat less than typical based on PEG’s prior experience.

The Palm Desert air conditioners were oversized by 63% on average, while the Cathedral City units were only oversized by 20%. The most severe oversizing was found in the two houses with 5 ton air conditioners which were 85% and 95% oversized. The installed units varied much more in size than the small differences in design loads would indicate. The calulations indicate that 3 ton air conditioners would probably be sufficient for all of these houses.

SUMMARY OF FIELD FINDINGS

The new homes in this sample are fairly small and have reasonably tight building shells and duct systems, with the notable exception of the return systems in the one story houses. The measured supply duct leakage averaged 9.5% of the air handler flow in the one story houses and 4.1% in the two story houses. Return leakage was more than twice as large, averaging 20.8% and 11.6% in the two types of houses respectively. The air conditioners are oversized, particularly in the larger houses and the two story houses. The systems also suffered from low air flow due primarily to undersized return ducts. These findings are generally consistent with similar investigations performed elsewhere (See Appendix A).

Refrigerant charge could not be assessed due to lack of 220V power at the sites. However, prior studies in California and Nevada indicate that, in newly built houses, half of the systems are usually overcharged and a quarter undercharged. This issue is addressed through modeling.

Table 2-2 summarizes the key results from the field investigation.

Table 2-2 Field Investigation Results

	Duct Leakage Rates				**Bldg Lkg**	**Loads**	**Air Conditioner**			
	CFM @ 50pa		Oper. Ext. Lkg % of flow		Shell	Manual J	Air Flow	Capacity		Sizing
ID	Total	Exterior	Supply	Return	CFM @50	Design @ 110/75	CFM / ton	Rated @ 95/80	Rated @ 110/75	% of Proper
CC1	586	497	10.2%	19.9%	1675	26088	N/A	45000	33625	129%
CC2	562	465	11.2%	24.3%	2000	26669	N/A	41500	31010	116%
CC3	581	501	11.7%	19.2%	1900	30930	317	45000	33625	109%
CC4	450	403	7.3%	25.7%	1525	26669	348	41500	31010	116%
CC5	423	339	7.2%	15.0%	1350	26088	336	45000	33625	129%
PD6	291	228	8.7%	12.9%	2650	21641	330	42000	31383	145%
PD7	305	186	6.4%	12.2%	2350	21470	352	42000	31383	146%
PD8	214	108	1.7%	13.5%	2300	21232	253	55500	41471	195%
PD9	184	94	2.7%	8.2%	1750	21791	321	42000	31383	144%
PD10	196	102	1.2%	11.2%	2200	22472	297	55500	41471	185%
Avg. All	379	292	6.8%	16.2%	1970	24505	319	45500	33999	141%
Avg. CC	520	441	9.5%	20.8%	1690	27289	334	43600	32579	120%
Avg. PD	238	143	4.1%	11.6%	2250	21721	311	47400	35418	163%

ACHIEVABLE IMPROVEMENTS AND THEIR COSTS

Once the nature and extent of the problems were defined in the field investigation, PEG staff investigated the realistically achievable improvements that could be made to the duct and air conditioning systems and the associated costs. Improvements examined include: sealing the ducts, using better insulated ducts, properly installing and testing the air conditioner, and increasing the peak EER of the air conditioner by two points.

- The additional time and materials needed to properly seal the systems with mastic and ties is estimated at $95 per system, $50 for materials and $45 for 1 hour of extra labor. Based on prior experience with systems in California, Florida, and North Carolina, PEG estimates that total duct leakage of 75 CFM25 per system is realistically achievable on every new unit[3]. This opportunity is effectively lost if the ducts are not sealed when the house is being built. On a retrofit basis, the cost would exceed $200 and the systems could not be made as tight.
- The extra cost for doubling the insulation level to R-8 is estimated at about $140 per house (based on previous PEG research).
- Proper installation and testing of an air conditioner (including proper evacuation, proper charge, checking capacity and EER) requires an extra 1.5 hours per system, yielding an incremental cost of about $68. There may be material savings from using less refrigerant.
- Using a properly sized air conditioner (about one ton reduction after system improvements) will save $100 per air conditioner.
- The incremental cost of an air conditioner with a two point higher peak EER[4] is estimated at $350 per system based on price quotes from 5 manufacturers.

The benefits of these potential improvements were assessed through detailed modeling of air conditioner and duct performance.

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[3] Researchers and practitioners have a variety of opinions on the proper specification. Some argue for a more stringent standard based on the potential gains from a well sealed distribution system. Some argue for a less stringent standard based on the level of success they have had while using contractors with little training and little or no follow up. PEG believes that 75 CFM25 is a standard that is achievable using "typical" contractors, if adequate training and follow up are supplied. A more stringent standard could be met with significant sealing of the air handler. (75 CFM25 is approximately equal to 118 CFM50)

[4] Peak EER and SEER are not equivalent. Peak load reductions are not assured by increasing SEER. (SOURCE: Proctor, et al, 1994)

MODELING IMPACTS ON USAGE & PEAK DEMAND

The field investigation found opportunities for potentially significant improvements to the cooling systems. Assessing the impacts of the identified problems and their solutions on energy usage and peak demand requires an analysis which models the air conditioner, duct system, and building shell and incorporates the interactions between them. For example, when a leaky return draws air from the attic it raises the temperature at the inlet to the indoor coil resulting in an increase in air conditioner capacity and watt draw. PEG has adapted the Palmiter Duct Model (Palmiter and Bond, 1991) and created an AC model for dry climate performance. These models are combined into a comprehensive model that incorporates many of the complex interactions in the systems studied. The model calculates system efficiencies, losses, loads, energy usage, and demand at a series of outdoor temperature bins based on a typical weather year in Palm Springs.

A realistic analysis of peak demand impact also requires characterizing the effect of occupant behavior patterns on actual cooling demand. PEG has developed a model which utilizes submetered air conditioner data to characterize the interactions between occupant behavior patterns/cooling load and effective capacity. This peak model (Model P) significantly improves upon most existing peak models which usually employ a single general residential AC demand curve.

AIR CONDITIONER PERFORMANCE MODELING

Air conditioner performance can be characterized at given conditions by system capacity and EER. These two quantities can be used to calculate the power draw and, along with air handler flow rate, the temperature drop across the indoor coil. System capacity is modeled as a function of outdoor temperature, return plenum temperature, air handler flow rate, and charge. The model assumes a nearly dry coil given local climate. EER is modeled as a function of outdoor temperature, return plenum temperature and charge. The air conditioner model return plenum temperature is calculated from the duct system model.

For both capacity and EER, each factor effecting performance is represented as a multiplicative adjustment to the rated value. The adjustment factors are based on available published data and studies by PEG. This model is discussed in Appendix B.

DUCT EFFICIENCY MODELING

The impacts of duct leakage and conduction on effective system efficiency and building loads are complex. Duct leakage can cause four types of efficiency losses:

- the supply air that leaks to the exterior is a direct efficiency loss;
- the return air coming from outside and spaces warmer than outside (e.g. the attic) adds to building loads;
- the supply and return flows increase the air leakage rate of the building shell depending upon the relative size of the flows and the building's natural infiltration rate;
- when the air handler is off, the duct leaks still add to the building shell leakage rate.

Each of these effects is accounted for in the duct efficiency model. The duct leakage model inputs include the supply and return leak fractions (as a percentage of the air handler flow rate[5]), the temperature of the air surrounding the return ducts, and the natural air leakage rate of the building shell (based on the blower door test and a limited implementation of the LBL infiltration model).

Conductive heat gain into the ducts is modeled as a function of duct area, R-values, the temperature of the air around the ducts (which depends on outdoor temperature and duct location), and the temperature of the air in the ducts (which depends on the air conditioner capacity, duct air flow, and duct leakage rate). Conductive heat gain to the ducts is assumed to occur simultaneously with system operation (i.e., no losses during off-cycle, full load losses during entire operating time). This approach makes efficiency losses due to duct conduction dependent on the capacity of the air conditioner and as such are dependent on the relationship between the load, capacity, and duct size.

The leakage and conduction models interact in terms of calculating return plenum and average supply duct temperatures and in avoiding any "double-counting" (e.g., the efficiency loss due to conductive gains into the portion of supply air which leaks out of the ducts is not included).

ENERGY USAGE MODELING

All of the duct-related losses are expressed in terms of percentage efficiency losses to the air conditioning system. The effective capacity of the air conditioner is calculated as the system capacity at given conditions adjusted for duct efficiency losses. The building

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[5] Because duct leakage rates are specified as a percentage of the air handler flow rate, an increase in system air flow leads to an increase in duct leakage. This approach assumes that air handler flows are increased through means which increase static pressures in the ducts (e.g. increasing fan speed), not decrease static pressure (e.g. by increasing the size of the ducts).

shell load is calculated as a piece-wise linear response to outdoor temperature (with an elbow at design conditions). The effective capacity and the building shell load are used to calculate the duty cycle, which is used to calculate the hourly energy usage (adjusted for cycling losses). These calculations are performed at each of several different outdoor temperature bins and the results are combined by weighting by the number of hours at that temperature each year in Palm Springs to arrive at an annual energy usage rate. The energy usage model assumes that all units are controlled by a constant thermostat setting (75°F). Occupant interactions are not included in the energy usage model, but are a key component of the peak demand model.

PEAK DEMAND MODELING (MODEL P)

The diversified demand of air conditioning systems during system peak involves more than simply modeling performance and efficiency during peak conditions. Occupant behavior patterns can have a large influence on actual demand during peak. Some households (referred to as Group A) have no air conditioning use during peak. These homes may be unoccupied at that time or the occupants have the air conditioner switched off. Other households may have the air conditioner running continuously (Group D), often because the occupants have recently adjusted the thermostat down. Another group of households (Group B) have their air conditioners cycling on and off based on thermostatic control. Some households may have a constant thermostat setting in the period of interest but the effective capacity of their air conditioning system is less than the load. These households (Group C) have air conditioners running continuously, but some achievable reduction in load or increase in effective capacity would result in them cycling. The proportion of households in each of these categories must be estimated to arrive at reasonable estimates of diversified peak demand.

PEG received a sample of load research data from SCE in order to estimate the proportion of households in each of the above customer groups during system and residential peak times (system peak is at 3-4 PM on hot weekdays, residential peak is 5-6 PM on the same days). The load data is from a random sample of twenty existing residential customers. These customers may or may not represent the new construction market in terms of demographics, behavior patterns, building shell characteristics, or air conditioning equipment. Eleven of these customers have one air conditioner (like the houses in the field investigation), the remaining nine have more than one unit and were eliminated from this analysis. The data set is from the summer of 1994 and includes five very hot days which are typical of system peak conditions (outdoor temperatures reaching 113ºF-116ºF). PEG analyzed this data and classified each customer-peak hour into one of the four groups. The average duty cycle of Group B customers on peak hours was also analyzed. The percentage of customers in each class is shown in Figure 4-1.

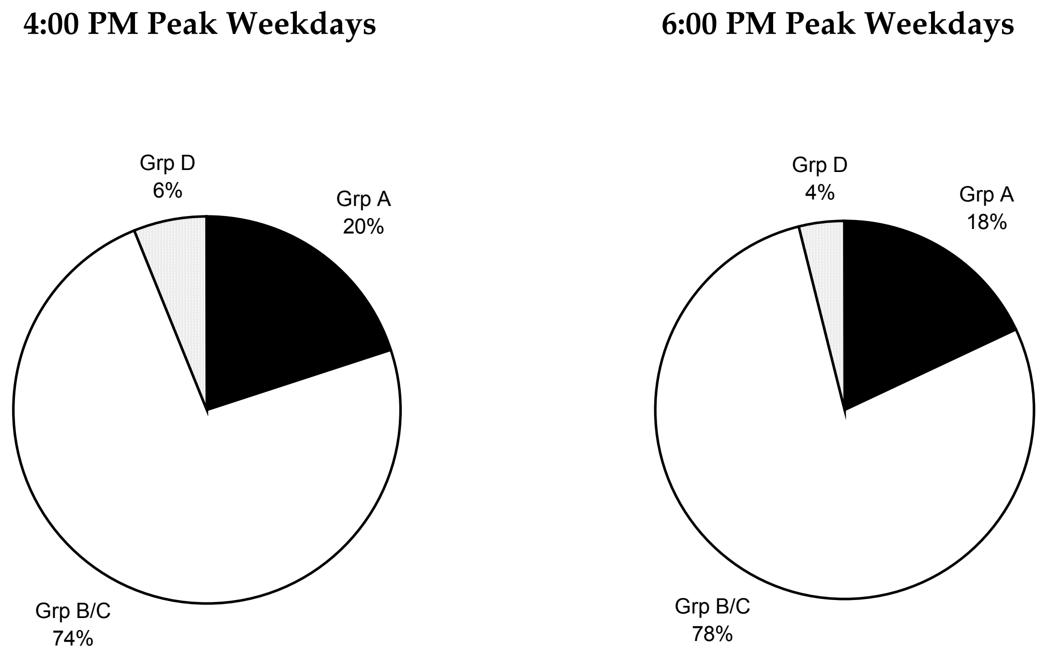

Figure 4-1
Model P Classes from Submetered Sample

Customers in this sample show a much smaller percentage in Group D (continuous running) that previous samples examined by Proctor Engineering Group. It is possible that Palm Springs Area residents are more likely to keep a constant thermostat setting than people in other locations.

The actual cooling loads for the new houses inspected in this project are not known. However, when the effective capacity equals the actual load, the duty cycle of the equipment will be 100%. For homes that are in Class B/C, the underlying duty cycle at 116°F was 69% in the metered sample. This information was incorporated into the model by scaling the load estimates to produce an underlying duty cycle equal to 69%. The sensitivity of the model results to building cooling loads was assessed by also performing all model runs at a ten percent higher duty cycle (79). The group data used in the model are summarized in Table 4-1.

Table 4-1
Model P Classes Used in Peak Demand Model

	Group A System Off		Group B/C Cycling or could cycle		Group D Continuous	
	4 PM	6 PM	4 PM	6 PM	4 PM	6 PM
Underlying Duty Cycle - loads scaled to match metered sample	0%		69.0%	(61.6%)	100%	
Underlying Duty Cycle - higher scaled loads	0%		79.0%	(71.6%)	100%	
Percent of Customers	20.0%	18.2%	74.5%	78.2%	5.5%	3.6%

The data in the table are used to adjust the system modeling results by Model P class. The diversified demand is calculated as the weighted sum of the demands of the four groups. Group A households have no demand at peak. Group D households' demand equals their modeled connected load. Group B and C households are in a constant thermostat setting mode and their duty cycle changes as different scenarios are modeled. This approach is discussed further in Appendix B.

SUMMARY OF MODEL INPUTS

The cooling model requires information on numerous aspects of the air conditioner, the duct system and its surroundings, and the building shell. Table 4-2 describes the inputs and the sources used in this project. A more detailed description of the model and data sources is provided in Appendix B.

Table 4-2
Model Inputs & Data Sources

Category	Model Input	Source / Assumption
Temperatures	Outdoor Temperature	Bin data for Palm Springs, peak of 116°F
	Indoor Temperature	Assumed at 75°F
	Temperature surrounding ducts	weighted average of outdoor and attic temperatures (assumed 20°F higher than outdoor) based on field-estimated location breakdown for supply and return
	Temperature of infiltrating air	assumed 40% from attic, 60% from exterior
Duct System	Supply & return leakage fractions	based on Duct Blaster™ tests, air flow test, and operating pressure measurements
	Duct leakage % of shell leakage	based on Duct Blaster™ test and blower door test
	Duct Area (square feet.)	based on # of runs, sizes
	Duct R-Value	R-4 based on insulation thickness
Air Conditioner	Rated capacity & EER	from nameplate information and published values
	Air Handler Flow	from field tests using Duct Blaster as powered flow hood
	Charge	scenarios modeled include systems 20% overcharged and 20% undercharged. Baseline assumes 50% are overcharged, 25% undercharged, 25% propoerly charged[6]
Building Shell	Cooling load	Design load adjusted to temp. diff. and tuned to metered sample peak duty cycle and duty cycle+10%
	Airtightness (CFM50)	from blower door test

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[6] An assumption of 20% under or over charge keeps the model within the range of known effects and is conservative relative to the level of incorrect charge that is often found in the field. The proportion of units over and undercharged is based on two studies of new construction which had similar results (see Appendix A).

MODELING RESULTS

When applied to the 10 systems tested in the field investigation (assuming 50% of units are overcharged and 25% undercharged), the energy and demand models predict an average annual cooling load of 2942kWh with 2.76 kW of diversified demand at system peak and 2.79 kW at residential peak. Duct-related efficiency losses average 33% of system capacity with 21% due to leakage and 12% due to conduction.

Air conditioner system air flow and charge problems account for 12% of usage and 3% of peak demand. Overcharged systems increase energy usage and peak demand by about 20%. Undercharged systems increase energy usage by about 24% and *decrease* peak demand by 7%.

The estimated impacts and costs of potential improvements to new residential construction in Palm Springs are summarized in Table 4-3. The demand reduction at residential peak (6:00PM) and from modeling performed with a higher assumed duty cycle are shown in Appendix C.

Table 4-3
Estimated Program Impacts & Costs

		Savings			
Program Design Elements	**Direct Cost**	**kWh**	**kWh%**	**Peak kW**	**kW%**
Baseline - Systems as found	0	2942		2.76	
A. Restrict Duct Leakage to 75 CFM25 total	$95	542	18%	0.62	22%
B. Duct Lkg 75 & R-8 Duct Insulation	$235	730	25%	0.83	30%
C. Correct AC charge and air flow rate	$68	353	12%	0.08	3%
D. Duct Lkg 75, Charge, Air flow	$163	817	28%	0.75	27%
E. Duct Lkg 75, R-8, Chg/flow	$303	958	33%	0.92	33%
F. EER 2 higher, Chg/flow	$418	805	27%	0.55	20%
G. All of the above	$653	1307	44%	1.24	45%

The table shows that there are a number of potentially attractive options for reducing cooling usage and peak demands at reasonable incremental costs. For example, Design B, which only improves the duct system, should save about 25% of the energy usage and reduce peak by about 30%. Design F, which involves the selection and installation of the air conditioner shows a 27% energy savings and 20% peak reduction. Design G, which includes all contemplated duct and air conditioner measures could reduce usage by as much as 44% and peak demand by 45 percent.

NOTES ON THE COMPREHENSIVE MODEL

The comprehensive model used in this study is unique in modeling many of the interactions between the ducts, air conditioner, and building shell. At the same time it, like all models, is based on simplifications of the systems involved. Additional research is needed on air conditioner performance in hot/dry climates under peak conditions, particularly with typical field conditions (other than "correct" charge and air flow).

Actual cooling loads are highly subject to customer interactions and only metered data can accurately determine the relationship between cooling demand and capacity. For that reason, cooling loads were modeled at two different levels. This sensitivity analysis showed that the percentage energy savings and peak reductions are only mildly affected by assumptions about cooling load within the expected range. For example, the energy savings under Design A (reduced duct leakage) changes from 18.4% to 17.7% (see Appendix C. The assumption of a constant 75°F thermostat setting and cooling loads that increase linearly with outdoor temperature[7] are simplifications that affect the absolute energy consumption estimates much more than the percentage savings. An analysis of hourly sub-metered usage patterns from similar newly-built houses could be used to "true-up" these percent savings estimates to typical usage levels.

The highest levels of savings are most subject to uncertainty because they result from complex interactions. Proctor Engineering Group recommends that these savings and peak reductions be verified by metering a sample of buildings.

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[7] The model assumes a cooling load (including solar gain) that increases linearly with outdoor temperature from 80°F to design (110°F). The cooling load above design is assumed to have a constant solar gain component and a conductive component that is linear with outdoor temperature.

CONCLUSIONS AND RECOMMENDATIONS

Newly constructed homes in the Palm Springs region of Southern California Edison's service territory have substantial deficiencies in their cooling systems, similar to those found in studies from other parts of the country. Moderate cost improvements can be achieved to lower energy usage and demand while improving occupant comfort and satisfaction.

CONCLUSIONS

- Duct leakage and existing duct insulation levels cause an average loss of 33% in overall cooling efficiency. Reasonable improvements can eliminate over half of these losses (saving 18% of the cooling energy) for about $235;
- A program which ensures tight, well-insulated ducts and properly installed efficient air conditioners could reduce cooling usage by approximately 44% and diversified system peak demand by 1.2 kW. The additional cost is estimated to be $650 per unit.

SCE has a variety of potentially worthwhile options for improving cooling efficiency and reducing peak demand. Proper program design, training, and quality assurance are critical issues for actually achieving these improvements.

RECOMMENDATIONS

1) Program implementation should begin with a number of submetered houses (comparison and experimental) to verify the model results and to determine the achievable level of capacity reduction.
2) Air handler manufacturers should be enlisted to work with utilities toward the common goal of building tighter air handling units, which are the cause of significant distribution system leaks and are outside the influence of the local installer;

The following additional research is recommended:

- Air conditioners on a sample of newly constructed homes in the Palm Springs area should be submetered. This can be combined with the first recommendation above.
- Air conditioner performance should be laboratory tested under a wide variety of operating conditions (air flow, charge, indoor temperature, and outdoor temperature) and system types. This would assist in modeling the air conditioner under peak conditions "typical" to Palm Springs.
- New construction air conditioner installation practices in the Palm Springs area should be observed. The results would allow refinement of program specifications.

APPENDIX B:
COMBINED MODEL AND DATA SOURCES

The combined model presented in this report is composed of three primary sub-models: a duct loss model, an air conditioner performance model, and a residential air conditioner peak load model.

A schematic of these three models is shown in Figure B-1

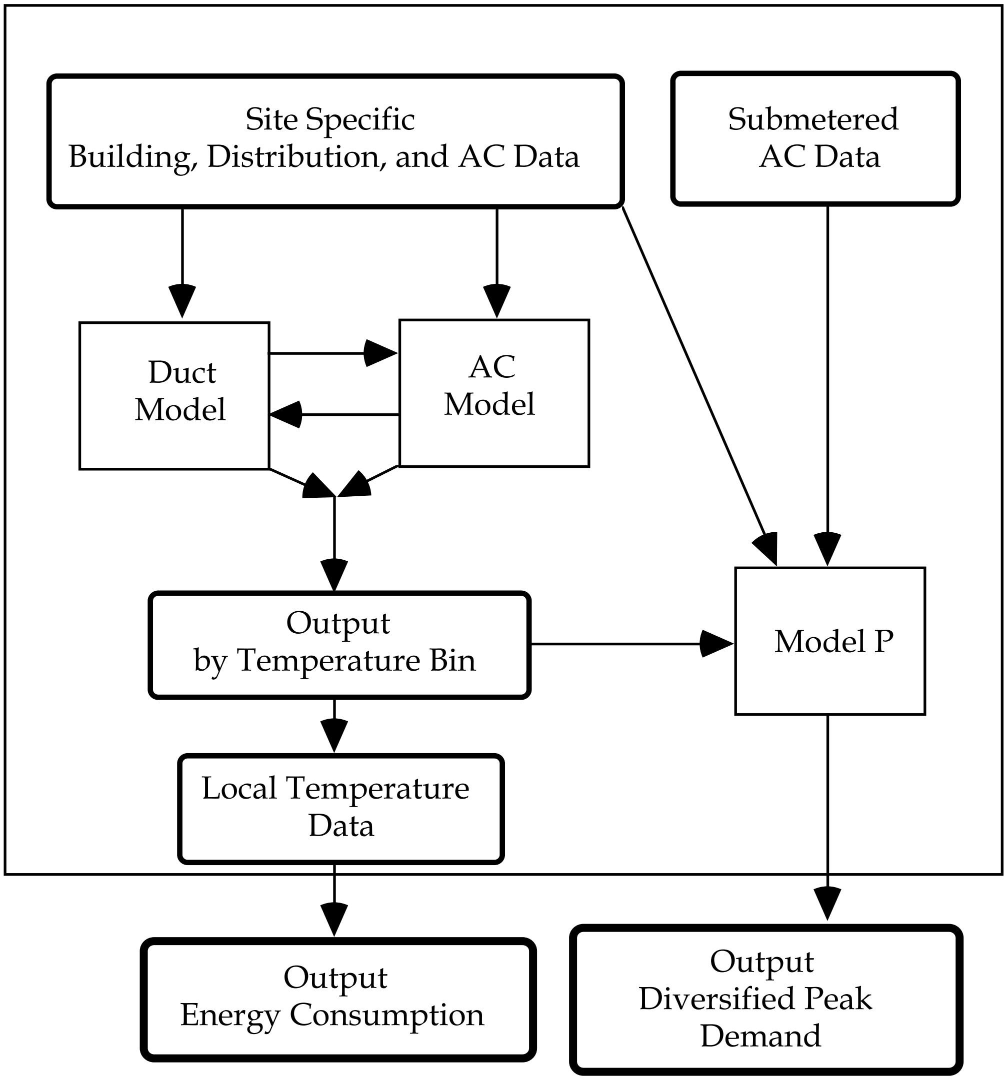

Figure B-1
Combined Model Schematic

DUCT LOSS MODEL

The duct loss model includes the impacts of direct leakage losses, induced building infiltration losses, and conductive losses. The model characterizes these losses as a loss of effective system capacity. The duct model also calculates return plenum temperatures and average supply air temperatures based on leakage and conduction rates and indoor and supply plenum temperatures.

The basic model including leakage and infiltration effects is the work of Palmiter (Palmiter and Bond, 1991). Proctor Engineering Group has added the effects of conduction and energy recovery (when supply leakage is mitigated by nearby return leaks and other recovery mechanisms) into that model.

The duct loss model is a steady state model. The losses are scaled to the duty cycle of the air conditioner for each temperature bin.

AIR CONDITIONER MODEL

The model calculates changes in capacity and efficiency due to:

- Outdoor temperature
- Refrigerant charge (capacity and efficiency generally peak at proper charge, but the effect is dependent on other variables)
- Return plenum wet bulb temperature (nearly dry coil)
- Return plenum dry bulb temperature
- Air flow across the indoor coil

The model also calculates the supply plenum air temperature based on the return plenum temperature, system capacity, and air flow rate.

The model draws on a variety of sources including:

- Laboratory tests of air conditioners with charge varied from 20% below to 20% above proper charge (Farazad and O'Neal, 1988 and 1989). These tests were conducted with outdoor coil inlet air temperatures from 82°F to 100°F.
- Simulation runs by Proctor Engineering Group for higher outdoor temperatures and lower indoor wet bulb conditions with MODCON, the air conditioner simulation program of Oak Ridge National Laboratory (Rice, 1991).
- Data gathered from major manufacturers on performance of air conditioners under nearly dry coil conditions.

The air conditioner model is a steady state model. The consumption is scaled by the duty cycle of the air conditioner for each temperature bin with an adjustment for cycling losses.

MODELED COOLING LOADS

Building shell loads for the combined energy consumption model were based on a constant temperature setting[12] of 75°F. These cooling loads (including solar gain) were assumed to increase linearly with temperature from 80°F to 110°F. The cooling load above 110°F was assumed to have a constant solar gain component and a conductive component that is linear with outdoor temperature. Building shell load was used to tune the model to match the average duty cycle of “thermostatically controlled” units in the submetered data. An alternative duty cycle 10% higher was also used to assess the sensitivity of the results to alternative cooling loads.

PEAK LOAD MODEL (MODEL P)

Model P includes all the impacts both known and unknown that effect occupant behavior to produce a given duty cycle at peak. These effects are nested in the empirical base for Model P - submetered air conditioner data from peak hours. The output from Model P is the diversified demand of the residential air conditioners under varying scenarios.

Model P divides residential air conditioners into four groups. Group A consists of air conditioners that are not operating on peak. On peak, Group B and C air conditioners cycled (Group B) or potentially cycled (Group C) by the thermostat. Group D air conditioners run constantly on peak and would do so even if substantial improvements were made in the effective capacity of the system. The breakdown of groups used in this study is shown in Figure B-2.

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[12] For the diversified peak load model (Model P) only a portion of the units were modeled as “thermostatically controlled” (Groups B and C).

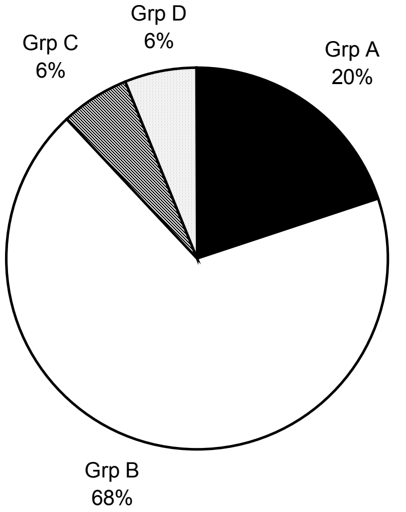

Figure B-2
Incidence of Model P Classes during system peak

The output from Model P is the diversified demand of the residential air conditioners under varying scenarios. The diversified demand is calculated as the weighted[13] sum of the demands of the four groups. The demand of the four groups are:

- Group A air conditioners have no demand at peak
- Group B and C air conditioners have a peak demand that is dependent on the ratio of the cooling load to the effective capacity of the unit (duty cycle). Under different scenarios, the duty cycle will change. The baseline condition for this study is an underlying duty cycle for B's and C's of 67.9%. The loads for the combined model were tuned to this duty cycle so the output from that model is the peak demand for Groups B and C.
- Group D demand equals their modeled connected load. The connected load (which is dependent on outdoor temperature, return plenum temperature, refrigerant charge, and indoor coil air flow) is an output from the combined air conditioning and duct model adjusted by the relative loads illustrated in Figure B-2.

Model P was developed by Proctor Engineering Group in order to improve predictions of peak effects from alternative technological options. The data used to build Model P for this study came from a sample of twenty randomly selected houses from an existing SCE load research project. Nine sites with more than one air conditioner were removed from the analysis because all of the field sites had just on unit. The remaining sites'

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[13] weighted by their occurrence in the submetered data

usage patterns from the five hottest days of 1994 were analyzed and characterized into the Model P groups.

The duty cycles for Groups B and C from the submetered data are distributed as shown in Figure B-3.

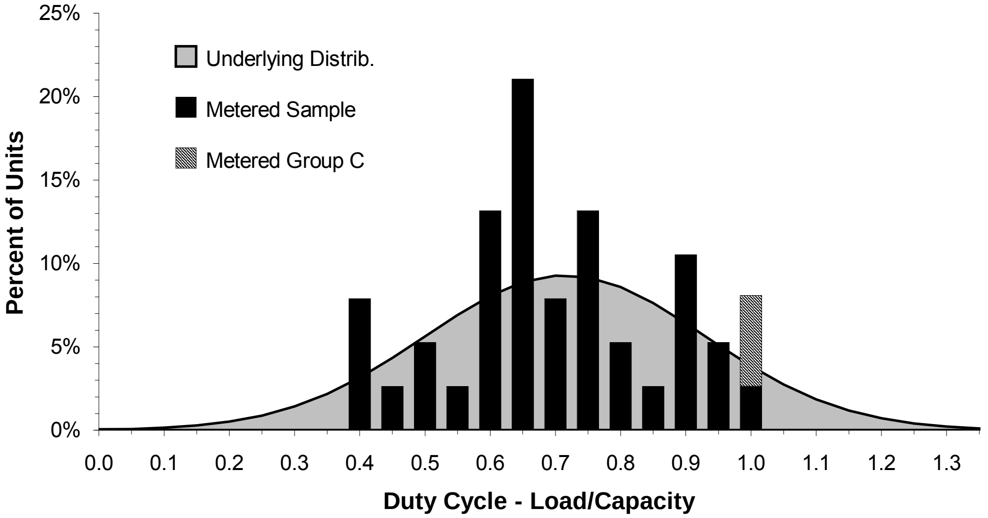

Figure B-3
Duty Cycle of Submetered Sample and Underlying Duty Cycle

The duty cycling rates for Groups B and C were used to estimate an underlying mean and standard deviation for a "normal" distribution that would approximate the observed duty cycles. The underlying mean for the baseline case was .690. The real duty cycle cannot exceed 1.0 (units that would have a duty cycle of greater than 1.0 are Group C) and therefore the "normal" curve is constrained to no greater than 1.0 giving a spike at that point. Reductions in load or increases in effective capacity will shift this distribution to the left, reducing the mean duty cycle and decreasing the percentage of units in Group C. The shift in the duty cycle distribution for Groups B and C is calculated using the combination duct/AC model.

APPENDIX C:
MODEL RUN DETAILS

Table C-1
Estimated Program Impacts & Costs: Higher Loads
(Underlying Duty Cycle = 79%)

Program Design Elements	Direct Cost	Savings			
		kWh	**kWh%**	**Peak kW**	**kW%**
Baseline - Systems as found	0	3345		3.01	
A. Restrict Duct Leakage to 75 CFM25 total	$95	592	18%	0.58	19%
B. Duct Lkg 75 & R-8 Duct Insulation	$235	804	24%	0.83	28%
C. Correct AC charge and air flow rate	$68	389	12%	0.01	0%
D. Duct Lkg 75, Charge, Air flow	$163	903	27%	0.73	24%
E. Duct Lkg 75, R-8, Chg/flow	$303	1065	32%	0.93	31%
F. EER 2 higher, Chg/flow	$418	906	27%	0.53	18%
G. All of the above	$653	1465	44%	1.30	43%